

Some Aspects of Inverse Compton Emission from 3K Background Photons

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Abstract. We review the history and a few features of IC/3K emission. We discuss observing strategies, the physical parameters which can be derived directly or indirectly from successful detections, and the disparities between magnetic field strength estimates found by different methods.

1. Introduction

The recent history of inverse Compton emission from cosmic background photons and relativistic electrons (IC/3K) began during the period when the origin of extended X-ray emission from clusters of galaxies was unclear. Felten and Morrison (1966), Blumenthal & Gould (1970), and Jones, O'Dell & Stein (1974) were among those who worked out the details of IC/3K, but not until iron lines were detected in the X-ray spectra was it generally accepted that the bulk of the X-ray emission was caused by the thermal bremsstrahlung process.

Although there were many attempts to isolate IC/3K emission from clusters, these were thwarted by the strong thermal emission which is quasi ubiquitous in clusters. The recent breakthrough came from the dual detections of IC/3K from the lobes of Fornax A: spatially with the ROSAT PSPC (Feigelson et al. 1995) and spectrally with ASCA (Kaneda et al. 1995). In the last two years, there have been papers published on other sources which are relatively free of hot gas emission and from cluster radio halos, both from EUV excesses and from the harder spectral component at energies for which the thermal X-rays are dropping exponentially.

2. Salient Features

In this section, we list a few of the attributes of IC/3K emission which are often overlooked.

2.1. Every non-thermal radio source also emits IC/3K emission

IC/3K emission is mandatory: every (non-thermal) radio source in the universe is an emitter. This statement entails

only the assumption that the 3K background is indeed universal. Thus the only problem is to see if it is strong enough for detection with a given system, and if it can be separated from other emissions.

2.2. Electron Energy and the observing frequency

At a given (X-ray) energy, we will be sampling the relativistic electron spectrum at the same value of electron energy (γ) for every source in the universe. This is because the peak frequency, ν_o , of the cosmic background spectrum (where the major contribution to the photon energy density occurs) increases as $(1+z)$. A given electron with Lorentz energy, γ , emits most of its radiation at $\gamma^2 \times \nu_o$ and the emitted photons at that energy are redshifted by $(1+z)$ when observed on Earth. Thus soft X-rays (1-2 keV) sample $\gamma \approx 1000$ no matter what the redshift. Attempts to integrate these electrons in order to explain a significant part of the soft X-ray background have not been successful.

2.3. The importance of determining the amplitude of the electron spectrum at low energies

For $B < 5\mu\text{G}$, low energy electrons (e.g. $\gamma < 1000$) are not visible via their synchrotron (radio) emission because the ionosphere blocks frequencies below ≈ 20 MHz. Since these electrons normally have long lifetimes in the weak magnetic fields typically found in extended radio sources, they accumulate over the life of a radio source. In a sense we are sampling an encapsulated history of the radio source: the electron spectrum at low energies tells us about all the electrons produced over the source's lifetime.

3. Observing Strategies - avoid hot gas!

- By going to higher energy: e.g. BeppoSax and RXTE
- By getting outside clusters: e.g. Fornax A lobes and relic radio galaxies such as 0917+75 (Harris et al. 1995).
- Choose radio sources with large numbers of low energy electrons. This can be achieved by choosing sources

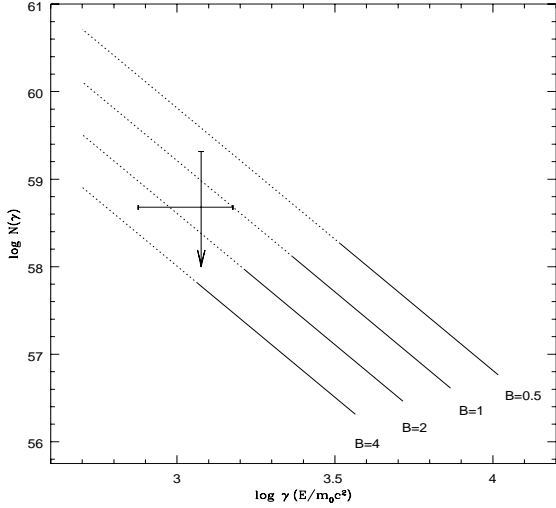


Fig. 1. Constraints on the electron spectrum for the relic radio galaxy, 0917+75 (taken from Harris et al. 1995). Heavy lines show possible segments of the electron spectrum, each labelled with a trial value of the magnetic field strength (in μG). The ROSAT derived upper limit is the only firm datum.

likely to have relatively more low energy electrons and to have weak magnetic fields since these require more electrons to get a given radio intensity. Therefore, steep spectrum, low brightness radio sources are best.

4. Rewards

Although most of us like to believe that a successful detection of IC/3K yields the average magnetic field strength directly, what we really measure is the amplitude of the electron spectrum at some low energy. To obtain the average field strength, there is still the uncertainty of the form of the electron spectrum between the direct measurement afforded by the IC/3K observation and the segment of the electron spectrum responsible for the radio emission. This is illustrated in figure 1. Since we can't be sure that a single power law extrapolates from the radio derived segment of the spectrum to the X-ray derived amplitude, the average value of B is uncertain (even if the ROSAT point were not an upper limit).

The electron spectrum below $\gamma=1000$ is of particular interest because in weak field regions (and $z<0.5$), E^2 halflives can approach 10^9 yr. Therefore, the total number of electrons in this energy range serves as a diagnostic of the total energy of a source during its life. While soft X-rays (e.g. 1.5 keV) provide a direct measurement of the number of electrons at $\gamma=1000$, EUVE data can provide estimates at $\gamma=300$. In Table 1 we have calculated $\log N$ ($100 < \gamma < 1000$) for a variety of radio sources by extrapolating their observed spectra to lower energies.

Table 1 Number of low energy electrons from extrapolated radio spectra

Source	Component	z	α_r	$B(\text{eq})$ (μG)	$\log V$ (cm^3)	$\log N$	τ (yrs)
FRII Cyg A	2 lobes	0.057	0.6	25	69.83	63.59	1E7
RELICS 0917	total	0.12	1.0	0.7	72.77	64.23	8E8
Coma	total	1.18	0.3	0.3	72.19	64.53	1E9
CenB	1 lobe	0.012	0.8	1.5	71.14	63.32	9E8
1358+30		0.11	0.72	0.9	72.00	63.22	8E8
1401-33		0.0136	1.44	8	71.67	64.91	1E9
3C 326	giantRG	0.089	0.82	0.8	73.46	64.75	9E8
IC2476		0.027	1.1	0.7	71.57	63.80	1E9
FRI 3C 31		0.016	0.63	1.5	70.61	61.97	9E8
0715	1arm	0.07	1.1	4	...	62.40	...
1718	halo	0.162	1.3	6	...	62.90	...
HALOS Coma	total	0.023	1.34	0.5	72.64	65.28	1E9

Notes to Table 1

z is the redshift

α_r is the radio spectral index

$B(\text{eq})$ is the equipartition field

V is the source volume

N is the integrated number of electrons for $100 < \gamma < 1000$

τ is the halflife for $\gamma=1000$ electrons.

While there are considerable uncertainties on the magnetic field and volume estimates, a substantial difference is seen for $\log N$ amongst Cyg A and relics; FRIs; and the Coma halo. These values support the notion that the relics were once FR II radio galaxies and that if cluster halos arise from the remnants of FR I galaxies such as tailed radio galaxies, it would require of order 1000 such contributions in 10^9 years.

Once an estimate of the average magnetic field strength is obtained, inferences can be made on the total energy density, $u(\text{tot})$, and thus on the composition of the relativistic particles. There are two contributions to the particle energy density, $u(p)$, which are not 'counted' by the radio observations: low energy electrons and relativistic protons. For low brightness radio sources, it is probably the case that most of the source is 'relaxed' in the sense that there are not active shock regions (e.g. hotspots) and equipartition between magnetic field energy density, $u(B)$, and $u(p)$ is a reasonable expectation. Thus knowledge of $u(B)$ translates to an estimate of $u(p)$ and $u(\text{tot})$. If the required $u(p)$ is large enough, the presence of relativistic protons may be indicated. The major uncertainty in this process is probably the unknown filling factor, ϕ , and if ϕ is substantially less than unity, the additional question: "Do the particles and field occupy the same volume?".

5. Discussion

5.1. Distinction between radio lobes (including relics) and cluster halos

While we have some evidence that relativistic and thermal plasmas are spatially distinct in the case of lobes of radio galaxies (e.g. Cygnus A, Carilli et al. 1994), we do

not have any confidence as to the situation for cluster halos. This is partly caused by the uncertainty concerning the genesis of radio halos in clusters. If relativistic plasma is completely mixed with the thermal plasma, then it is reasonable to assign a value close to unity for the filling factor, ϕ , but if the actual synchrotron emitting regions are to be distinct from the thermal plasma (in the sense of a magnetic boundary separating the two), then ϕ is most likely quite small. In the former case we should probably include the thermal energy density in any application of the equipartition condition, whereas in the latter case, we would be justified in balancing the relativistic particle energy density with the magnetic field energy density.

In a sense, we have two distinct problems. For relics and radio lobes such as Fornax A, we do not have to contend with excessive thermal emission and can get a fairly clean measurement if IC/3K intensity and distribution. But for clusters, it is only with difficulty that we avoid the thermal contamination.

What are the implications of the fact that some estimates of the Coma field strength are in reasonable accord with the minimum energy B field for $\phi=1$ and $u(p)=u(B)$? If the synchrotron emitting plasma were distinct from the cluster gas and $\phi \ll 1$, then the equipartition field B_{eq} would be much larger than the IC/3K estimate, and that does not seem to be the case.

5.2. Current IC/3K detections and the implied B fields

Using the relationships of Harris & Grindlay (1979), we have calculated the value of the average magnetic field strengths in some of the sources for which IC/3K detections have been claimed or an upper limit has been measured. These are presented in Table 2 together with magnetic field estimates published by the authors.

5.3. Comparison of B field estimates

The B field estimates for clusters discussed at this workshop can be roughly divided into 3 categories, depending on the method used and the type of source.

B=0.1 to 0.2 μG

These sorts of values were put forward on the basis of the excess X-ray flux observed over that expected from the hot gas in the Coma cluster. Both the EUV excess and the BeppoSax measurements yield B values $< 0.2 \mu\text{G}$. Fusco-Femiano et al. (1999) give $f_{\text{x}}(20\text{-}80\text{keV}) = 2.2 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and $B \approx 0.15 \mu\text{G}$. Note however that Henriksen (1998) using ASCA and HEAO-I data obtained an upper limit of $f_{\text{x}}(20\text{-}60\text{keV}) < 2.9 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}$ and $B > 0.26 \mu\text{G}$.

B \approx few μG

Magnetic field strengths of a few μG have been derived from equipartition calculations for the Coma radio halo, from the IC/3K estimates for the lobes of Fornax A, and from some estimates for clusters from Faraday rotation.

B = 5 to 20 μG

These stronger B field estimates generally come from the Faraday rotation measurements of unresolved sources in or behind clusters. The greatest uncertainty here is the scale size of magnetic field cells (for which the fields can reverse direction). If there are a large number of cells along the line of sight which have sufficient field strength and electron density to make a substantial contribution to the Faraday rotation, then the required B field will be significantly larger than for the case of only a few cells.

While we are not in a position to resolve the disparity in these B field estimates, we suspect that typical field strengths in clusters and relaxed radio lobes probably lie within the range $0.5 < B < 3 \mu\text{G}$. If this were to be the case, then published EUV and hard X-ray excesses are either wrong or arise from an emission process other than IC/3K and clusters have large scale coherent fields so that there are relatively few field reversals along the line of sight.

6. Conclusion

We have a fairly good idea of the problems involved in using IC/3K emission to derive physical quantities. Most of these difficulties are not going to go away soon, but the quality of the X-ray data should improve significantly with the advent of several missions with larger collecting area, better resolution, and extended frequency coverage.

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Table 2 Magnetic field estimates from IC/3K detections

		Luminosities			B Fields(A)		B Fields(RX)	
		Log Lr	Log Lx	Lr/Lx	B(eq)	B(ic)	B(eq)	B(ic)
		(erg/s)			(μ G)		(μ G)	
CLUSTERS								
Coma 1		40.85	43.71	0.001	...	0.15	0.2	0.05
RADIO LOBES								
Fornax A								
	Keast	41.40	40.95	3.24	...	2.4	1.0	1.8
	Kwest	41.64	40.89	5.62	...	3.5	1.0	2.6
	Fwest	41.78	41.08	5.01	3.0	1.9	1.4	2.0
RELICS								
A 85	0038-096	41.80	42.95	0.07	...	0.9	2.2	0.4
Cen B	<lobe>	42.20	41.50	5.01	...	3.1	1.4	1.7
0917	total	41.83	<42.30	>0.34	0.7	>0.7	0.7	>0.7

Notes to Table 2

Luminosities are indicative; the radio band was generally 10^7 to 10^{10} Hz (except as noted below). The X-ray bands depend on the telescopes used. B(eq) is the equipartition field (filling factor of unity and no protons) and B(ic) is the field strength derived from the IC/3K measurements. Both the original authors' values (A) and those calculated from the equations in Harris and Grindlay (1979) ['RX'] are given.

COMA 1

Entries are based on the composite radio spectrum presented by Fusco-Femiano et al. (1999); 'FF' hereafter. The general properties of the radio spectrum of the halo were checked against earlier presentations. Note however that whereas earlier work found α_r around 1.2 to 1.3, FF argue for curvature above 100 MHz, thus deducing a spectral break with an injection spectrum characterized by $\alpha=0.96$. For RX inputs, we take the synchrotron band to be 30-630MHz, with a fiducial flux density of $S(100\text{MHz})=10$ Jy (from their figure). The X-ray data are from BeppoSax (ibid.). FF combine two detector results and make a spectral fit with two components (thermal and a power law). For the power law, they get $\alpha_x = 0.6 \pm 0.4$. For the volume, we take the diameter used by FF: 25' (1 Mpc).

Fornax A

We used two papers: Kaneda et al. (1995) - ASCA spectral analysis ("Keast" and "Kwest"), and Feigelson et al. (1995)- spatial analysis from the ROSAT PSPC. Feigelson only did the West lobe ("Fwest").

A85

The results are based on Bagchi et al. (1998) from a wavelet analysis of ROSAT PSPC data.

CENTAURUS B (a.k.a. PKS1343-601)

This is a relic radio galaxy, somewhat obscured by the Milky Way. Radio data are from McAdam (1991) and the X-ray data are from Tashiro et al. (1998). Since the X-ray data are for the entire source, and since the lobes are not the same size and brightness, we model an 'average lobe', taking the size, $r=300''$ (that of the S lobe), and divide both radio and X-ray fluxes by 2.